A 3-dimensional accuracy analysis of chairside CAD/CAM milling processes

Bosch, Gabriel ; Ender, Andreas ; Mehl, Albert

Abstract: STATEMENT OF PROBLEM Milling is a central and important aspect of computer-aided design and computer-aided manufacturing (CAD/CAM) technology. High milling accuracy reduces the time needed to adapt the workpiece and provides restorations with better longevity and esthetic appeal. The influence of different milling processes on the accuracy of milled restorations has not yet been reviewed. PURPOSE The purpose of this study was to investigate the influence of different milling processes on the accuracy of ceramic restorations. MATERIAL AND METHODS Four groups of partial crowns were milled (each n=17): Three groups in a 4-axial milling unit: (1) 1-step mode and Step Bur 12S (12S), (2) 1-step mode and Step Bur 12 (1Step), (3) 2-step mode and Step Bur 12 (2Step), and (4) one group in a 5-axial milling unit (5axis). The milled occlusal and inner surfaces were scanned and superimposed over the digital data sets of calculated restorations with specialized difference analysis software. The trueness of each restoration and each group was measured. One-way ANOVA with a post hoc Tukey test was used to compare the data (=.05). RESULTS The highest trueness for the inner surface was achieved in group 5axis (trueness, 41 ±15 m, P<.05). The 4-axial milling unit exhibited trueness at settings ranging from 61 m (2Step) to 96 m (12S). For the occlusal surface, the highest trueness was achieved with group 5axis (trueness, 42 ±10 m). The 4-axial milling unit exhibited trueness at settings ranging from 55 m (1Step) to 76 m (12S). CONCLUSIONS Restorations milled with a 5-axial milling unit have a higher trueness than those milled with a 4-axial milling unit. A rotary cutting instrument with a smaller diameter results in a more accurate milling process. The 2-step mode is not significantly better than the 1-step mode.

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A 3-dimensional accuracy analysis of chairside CAD/CAM milling processes

Gabriel Bosch, med dent,[a] Andreas Ender, Dr med dent,[b] Albert Mehl, *Prof Dr, Dr med dent*[c]

Center of Dental Medicine, University of Zürich, Zurich, Switzerland

[a]Research Assistant, Division for Computerized Restorative Dentistry.

[b]Research Assistant, Division for Computerized Restorative Dentistry.

[c]Head of Division, Division for Computerized Restorative Dentistry.

Corresponding author:

Gabriel Bosch

Division for Computerized Restorative Dentistry

Center of Dental Medicine

University of Zürich

Plattenstrasse 11

8032 Zürich

Switzerland

Phone: +41 44 634 03 10

Fax: +41 44 634 43 07

E-mail: gabriel.bosch@zzm.uzh.ch

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ABSTRACT

Statement of problem. Milling is a central and important aspect of current computer-aided design and computer-aided manufacturing (CAD/CAM) technology. High milling accuracy reduces the time needed to adapt the workpiece and provides restorations with better longevity and esthetic appeal. The influence of different milling processes on the accuracy of milled restorations has not yet been reviewed.

Purpose. The purpose of this study was to investigate the influence of different milling processes on the accuracy of ceramic restorations.

Material and methods. Four groups of partial crowns were milled (each n = 17): Three groups in a 4-axial milling unit: (I) 1-step mode and Step Bur 12S (12S), (II) 1-step mode and Step Bur 12 (1Step), (III) 2-step mode and Step Bur 12 (2Step), and (IV) one group in a 5-axial milling unit (5axis). The milled occlusal and inner surfaces were scanned and superimposed over the digital datasets of calculated restorations with specialized difference analysis software. The trueness of each restoration and each group was measured. One-way ANOVA with a post hoc Tukey test was used to compare the data (α=.05).

Results. The highest trueness for the inner surface was achieved in group 5axis (trueness, 41 ±15 µm, *P*<.05). The 4-axial milling unit exhibited trueness at settings ranging from 61 µm (2Step) to 96 µm (12S). For the occlusal surface, the highest trueness was achieved with group 5axis (trueness, 42 ±10 µm). The 4-axial milling unit exhibited trueness at settings ranging from 55 µm (1Step) to 76 µm (12S).

Conclusions. Restorations milled with a 5-axial milling unit have a higher trueness than those milled with a 4-axial milling unit. A rotary cutting instrument with a smaller diameter results in a more accurate milling process. The 2-step mode is not significantly better than the 1-step mode.

CLINICAL IMPLICATIONS

The aim of the milling process is to generate an exact copy of the digitally calculated restoration. The 5-axial milling unit came closer to the digitally calculated restoration than the 4-axial milling unit.

INTRODUCTION

Dental ceramics have proven longevity and remain the materials of choice for esthetic restorations.[1-5] Ceramic restorations can be produced in different ways, one of which involves computer-aided design and computer-aided manufacturing (CAD/CAM). The aim of CAD/CAM technology is standardized, reproducible production that is both efficient and accurate.[6]

Clinical long-term success depends on factors such as adequate cementation, restoration design, preparation design, and—importantly—the marginal and internal fit of the restoration to the tooth. An important step with regard to the fit of the restoration is the fabrication process. Ceramic crowns can be distorted during this process, which can negatively affect the fit and compromise the success of the restoration.[7-10] Important considerations are how accurate the milling process is and whether it damages the restoration.

CAD/CAM allows the dentist to work chairside and is the fastest way to produce individual ceramic restorations. Cerec (Sirona Dental Systems) is a well-known chairside-technology CAD/CAM system that has proven both reliable and efficient.[11-13] The optical scan-system (Cerec Bluecam; Sirona Dental Systems) has also been shown to produce reliable and highly accurate 3-dimensional digital impressions.[14-18] The adaption of the restoration to the preparation with regard to marginal and internal fit has been shown to be clinically reliable in numerous different studies.[19-23] However, marginal gap values range from 35 to 246 µm, and internal gaps range from 17 to 206 µm.[24] Relatively large internal gaps can result from the milling process,[25] but gaps of up to 150 µm are clinically tolerable.[26] The marginal gap differs with different CAD/CAM systems,[27-29] but with the development of milling machines, marginal gaps are becoming progressively smaller.[30]

The accuracy of fitting to the underlying tooth structure is an essential consideration and could affect the longevity of restorations.[31,32] Larger gaps are associated with accelerated plaque accumulation, secondary decay, marginal discoloration, exposure of the luting resin, dissolution of the cement, and increased risk of microleakage and microcracks.[33-35] When the marginal gap is bigger than 100 µm, removing excess cement is more difficult.[36] A restoration with inadequate fit may lead to marginal chipping, and even small chips can result in the late clinical failure of ceramic restorations.[37]

With the CAD/CAM technique, high-precision scans are possible, and the software can calculate a restoration with exact control over contact points and design. The aims of this study were to evaluate the trueness of different milling processes that use 2 different milling units by comparing the milled restoration with the original digital data-set, and to visualize the deviations and marginal chippings caused by the milling process. The primary null hypothesis was that no qualitative differences would be found between the 2 different milling devices investigated, or their respective milling processes.

MATERIAL AND METHODS

Seventeen clinical ceramic preparations were selected for this study (2 inlays with 2 surfaces, 5 inlays with 3 surfaces, 6 inlays with 4 surfaces, 4 onlays). All preparations were performed in accordance with the manufacturer's guidelines. The preparations were digitally copied using an intraoral scanning system (CEREC Bluecam; Sirona) and printed in acrylate polymer (Objet MED610; Objet Geometries GmbH) with a 3-dimensional printer (Objet Eden 260V; Objet Geometries GmbH).

The printed casts were lightly powdered (CEREC Optispray; Sirona Dental Systems), and all were scanned with a digital intraoral scanning system (CEREC Bluecam Connect, software version 4.03; Sirona Dental Systems) by the same experienced operator. The preparation border was defined, and then the dataset transferred to a CAD/CAM software (InLab 4.0, Software version 4.02; Sirona Dental Systems). The restorations were calculated and sent to the milling preview.

The 4 milling procedures investigated are displayed in Table 1. Groups 12S, 1Step, and 2Step were milled with a 4-axial milling unit (InLab MCXL; Sirona Dental Systems). This milling unit uses 2 instruments for the milling process: a Step Bur, milling only the inner surface and a Pointed Bur, milling only the outer surface of the restoration. The Step Bur is available in 2 diameters, Step Bur 12S (1.2 mm) and Step Bur 12 (1.0 mm). In group 12S, the restorations were milled with a Step Bur 12S and Cylindrical Pointed 12S milling instrument. In group 1Step, the restorations were milled with a Step Bur 12 and Cylindrical Pointed 12S instrument. In group 2Step, restorations were milled with a Step Bur 12 and Cylindrical Pointed 12S instrument by using a so-called 2-step milling procedure. For those 3 groups, the parameters for the restorations were set as follows: Spacer: 80, Marginal-Adhesive Gap: 60, Occlusal-Milling Offset: 0, Proximal-Contacts Strength: -50, Occlusal-Contacts Strength: 25, Minimal Thickness (Radial): No, Minimal Thickness (Occlusal): No, Margin Thickness: 20, Consider Instrument Geometry: Yes, Remove Undercuts: Yes.

In group Arctica, the restorations were milled with a 5-axial milling unit (Arctica; KaVo). The restorations were exported to Surface Tessellation Language files (STL , standard for CAD/CAM data exchange) with the manufacturer's recommended parameters as follows: Spacer: 20, Marginal-Adhesive Gap: 0, Occlusal-Milling Offset: 0, Proximal-Contacts Strength: -50, Occlusal-Contacts Strength: 25, Minimal Thickness (Radial): No, Minimal Thickness (Occlusal): No, Margin Thickness: 0, Consider Instrument Geometry: No, Remove Undercuts: Yes.

The STL files were then imported into the 5-axial CAM-software and milled without any further changes. For all test groups, the calculated milling surfaces of the restorations were exported as STL files for later comparison with the milled restorations.

After milling, the sprue was removed from the restorations and were placed in the printed casts without any further adjustments. All milled restorations were scanned with a 3-dimensional scanning system (Bluecam, InLab 4.0, software version 4.02; Sirona Dental Systems). Bluecam is a scanner with a trueness for single-tooth scans of ±19.2 µm.[17] The surfaces were lightly powdered (CEREC Optispray; Sirona Dental Systems), the restorations were scanned from the occlusal view, and the 3-dimensional data-sets were exported as STL files (occlusal surface comparison).

The milled restorations were then fixed to an object plate provided with reference grooves, with the inner surfaces of the restorations facing upward. The surfaces were lightly powdered (CEREC Optispray), scanned, and the 3D data sets were exported as STL files (inner surface comparison).

Within each group the scanned surfaces of the milled restorations were compared with the calculated milling surfaces with specialized difference analysis software (OraCheck 1.00.10; Cyfex). The software superimposes the STL files by using a best fit algorithm for closest point matching of both surfaces. The occlusal or inner surfaces were selected precisely and the restorations superimposed. The software calculated and measured the distance (positive or negative) from every surface point (approximately 20 000 per surface matching) from the milled to the original surface. The point-by-point difference values for each single superimposition were exported to an American Standard Code for Information Interchange (ASCII) text file (comma-separated values). All the calculated distances were imported to statistical software (IBM SPSS 19; IBM Corp). For each superimposition of 2 surfaces, the 10th and 90th percentiles were calculated. The metric value for the deviation between 2 surfaces was defined as the (90th–10th)/2 percentile (DM). This DM gives the level by which approximately 80% of the matched area has less negative and positive deviations. In the next step the mean value and the standard deviation of the DMs were calculated for each group. These mean values describe the trueness of the milling process in terms of the deviation from the calculated original data. A lower value indicates a more accurate milling process. To compare the different groups, 1-way analysis of variance (ANOVA) with the post hoc Tukey HSD test was used as a statistical test (α=.05).

All visual examinations of the differences between the original and the milled restorations were performed by the same experienced dentist by means of color-coded difference images with boundary values set from +100 µm to -100 µm. Separate aspects of the images were examined, as shown in Table II. Aspect 1 was the occlusal relief, aspect 2 was the fine structures in the inner surface, aspect 3 was the surfaces with an angle close to the insertion axis in the inner surface, and aspect 4 was the marginal area in the inner surface up to 100 µm from the outer edge. The different aspects were visually evaluated separately for each restoration in direct comparisons between all groups. For the comparison of each restoration (4 images), scores were assigned as follows: 1 for the best result, 4 for the worst result. Ranking was determined according to the amount of pink, green, and purple present. Pink indicates a loss of ≥100 µm of material, green indicates almost no deviation from the CAD data set, and purple indicates differences ≥100 µm larger than the original. The same score in different groups means no visual difference in quality. A ranking between the groups was calculated based on the sum of the restorations for each group, as shown in Table III.

RESULTS

The trueness results for all groups are displayed in Table IV. Figure 1 shows graphs of the means and standard deviations for trueness. Table V shows the groups that were statistically significantly different. For the occlusal area, df was 3 and F was 5.802. For the inner surface, df was 3 and F was 6.166. For all test groups, the trueness in the occlusal areas ranged from 42 µm to 76 µm and in the inner areas from 41 µm to 96 µm. Group Arctica exhibited the highest trueness in both areas, with 42 ±10 µm in the occlusal area and 41 ±15 µm in the inner surface. For the inner surface, group Arctica was statistically significantly better than group 12S ($P<.001$). For the occlusal surface, group Arctica was statistically significantly better than groups 2Step ($P=.029$) and 12S ($P=.001$). The difference images from group Arctica showed the most accurate results in all 4 aspects (Fig. 2D, Fig. 3D). Group 2Step yielded a trueness of 67 ±24 µm for the occlusal area and 61 ±22 µm for the inner surface. In both areas, group 2Step did not differ statistically significantly from group 1Step, but in the inner surface, it was statistically significantly better than group 12S (P=.040). The difference images show the second-best results in all 4 aspects (Fig. 2C, Fig. 3C). In aspect 1, the occlusal relief and in aspect 4, the marginal areas, the results for groups 1Step and 2Step were the same. Group 1Step yielded a trueness of 55 ±18 µm in the occlusal area and 67 ±20 µm in the inner surface. The difference images were close to the difference images of group 2Step (Fig. 2B, Fig. 3B). However, with regard to the fine structures in the inner surface in aspect 2 and to the surfaces with an angle close to the insertion axis in aspect 3, group 2Step was somewhat better. Group 12S exhibited the lowest trueness in the occlusal area, 76 ±40 µm, and in the inner surface, 96 ±68 µm. The difference images shown in Figure 2A and Figure 3A display the largest deviations compared to the CAD data set in all 4 aspects.

DISCUSSION

The trueness of chairside milling processes was examined in this in vitro study. However, drawing meaningful comparisons with previously reported research is problematic. In previous studies, the marginal and internal fit were measured. Conventional methods measure these parameters in only 1 or 2 dimensions, and they measure the gap between the restoration and die with microscopy at 2 to 150 points in 5 to 10 specimens per group. Additionally, previous studies have evaluated fit with the elastomeric putty-wash technique, with low-viscosity silicone to duplicate the cement space and evaluate it photometrically, or analyze it based on its density and weight.[24,25]

Achieving clinically relevant results may require between 50 and 230 measuring points.[38] Modern computer-aided techniques can better evaluate the fit of the restoration as they yield much more extensive and informative data in 3 dimensions.[39] Three-dimensional analysis has also proven valid and reliable.[40] In previous studies, the internal and marginal gaps have been examined with 3-dimensional analysis by superimposing scans of the die over scans of the inner surface from the ceramic crown, or by superimposing scans of the die over scans of the fit-checker on the die to measure the thickness of the fit-checker, which replicates the cement space.[24, 39] With an accurate intraoral scanning system, the fit of the restoration in the oral cavity depends on the milling process.[18] Thus, this study did not focus directly on the marginal and internal fit, but rather on the milling process. With better trueness in the milling process, a better fit is facilitated. An inaccurately milled restoration results in a poor fit, with numerous occlusal and proximal contacts, which evidently differs substantially from the contact points precisely determined by the CAD/CAM software. Correcting the contact points intraorally may negatively affect the esthetics of the restoration, the contact distribution, chairside time, and longevity.[31,32]

In this study, the point-by-point differences were measured between the digitally acquired data and the milled restoration caused by the milling process. With the method reported, the inner and outer surface could be measured in addition to the internal fit. Another advantage of this method is that unlike other methods, neither fit-checker nor several dies are required, making it easier and more fail-safe. The difference images facilitate direct visual feedback encompassing the entire restoration and make it possible to locate the more imprecise areas. Bluecam has been validated as being accurate for single-tooth scans, with a trueness of ±19.2 µm in this context and is sufficiently accurate for use in this measuring method.[17]

The 4-axial milling unit (Inlab MCXL; Sirona Dental Systems) uses the Step Bur for the inner area and the Cylinder Pointed Bur for the occlusal area. While milling, the rotation axis of the material holder is fixed to ensure that both instruments maintain an appropriate insertion axis.

In 2-Step mode, the restoration is milled in 2 cycles. In the first milling step, the restoration is milled with an additional material thickness of 0.3 mm at all surfaces. The second milling cycle removes the remaining 0.3 mm of material to get the final dimensions of the restoration. Instruments with a larger diameter (Step Bur 12S: 1.2 mm) can withstand more mill cycles and have a higher excavation rate than instruments with a smaller diameter (Step Bur 12: 1.0 mm). However, a small diameter is needed to ensure the accurate milling out of smaller and deeper structures. Importantly in this context, the 5-axial milling unit (Arctica; KaVo) incorporates several different instruments, with instrument diameters from 3.0 mm to 0.5 mm. Additionally, with an additional axis, surfaces with an angle close to the insertion axis can be processed more effectively and accurately. The different instruments available within the system make it possible to generate a more accurate relief with deeper fissures and more accurately milled pointed angles.

Provided that quality is not sacrificed, a more rapid milling process for chairside restorations is beneficial for both the dentist and the patient. Changing to smaller instruments and milling with more than 2 different instruments, or milling in several steps, takes time. The milling process with a 5-axial milling unit is slower than that with a 4-axial milling unit, and the 2-step mode requires more time than the 1-step mode. In this context, the faster milling process results in a less accurate restoration, more marginal chipping, reduced longevity, and the possible need to loop-in the restoration intraorally.

Future research should investigate the roughness of the edges of restorations milled with different milling strategies with the scanning electron microscope and the effect of several mill cycles with the same rotary instrument on milled restorations.

The limitations of this research were that only the trueness of the milling process was measured and not the influence of the discrepancy on the marginal and internal gap and that the precision of the milling process was not investigated with more instrument milling cycles. Scanning with the need to powder the surfaces introduces a certain error level. A scan without powder could reduce possible artifacts.

From the scanning process to the restoration design, the CAD/CAM process has proven accurate under optimal circumstances. The incorporation of an optimized milling process with instruments that have a small diameter may result in similar levels of accuracy and finished restorations with higher esthetics and better longevity.

CONCLUSIONS

Within the limitations of this in vitro study, restorations milled with a 5-axial milling unit exhibited the best quality and the highest trueness values. With regard to the 4-axial milling unit (InLab MCXL, Sirona Dental Systems), the 2-step mode was not significantly better than the 1-step mode. A rotary instrument with a smaller diameter resulted in more accurate milling.

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Table I. Test groups with different settings.

Group	**Rotary instrument**	**N**	**Milling unit**	**Milling option**
12S	Step Bur 12S	17	InLab MCXL	1-step
1Step	Step Bur 12	17	InLab MCXL	1-step
2Step	Step Bur 12	17	InLab MCXL	2-step
Arctica	Arctica Bur Set	17	Arctica	5-axis

Table II. Aspects for visual examination.

Aspect 1	Occlusal relief
Aspect 2	Fine structures in inner surface
Aspect 3	Surfaces with angle close to insertion axis in inner surface
Aspect 4	Marginal areas in inner surface up to 100 µm from outer edge

Table III. Ranking of visual examinations.

Ranking	**Step Bur 12S**	**Step Bur 12 – 1-step**	**Step Bur 12 – 2-step**	**Arctica**
Aspect 1	4	2	2	1
Aspect 2	4	3	2	1
Aspect 3	4	3	2	1
Aspect 4	4	2	2	1

1 = best results; same number = no difference

Table IV. Trueness for all test groups.

Trueness with (90%–10%)/2 percentile			
Group	**Process**	**Occlusal trueness**	**Inner surface trueness**
12S	MCXL - Bur 12S – 1-step	76 µm ±40 µm	96 µm ±68 µm
1Step	MCXL - Bur 12 – 1-step	55 µm ±18 µm	67 µm ±20 µm
2Step	MCXL - Bur 12 – 2-step	67 µm ±24 µm	61 µm ±22 µm
Arctica	Arctica	42 µm ±10 µm	41 µm ±15 µm

Table V. All test groups exhibiting statistically significant differences.

Inner surface differences	
	P
Arctica <–> Bur12S – 1Step	<.001
Bur12S <–> Bur12 – 2Step	.040
Occlusal surface differences	
	P
Arctica <–> Bur12 – 2Step	.029
Arctica <–> Bur12S – 1Step	.001

LEGENDS

Fig. 1. Trueness values and standard deviations for all test groups.

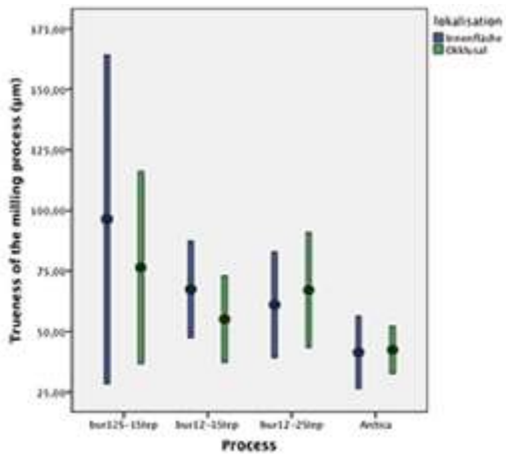
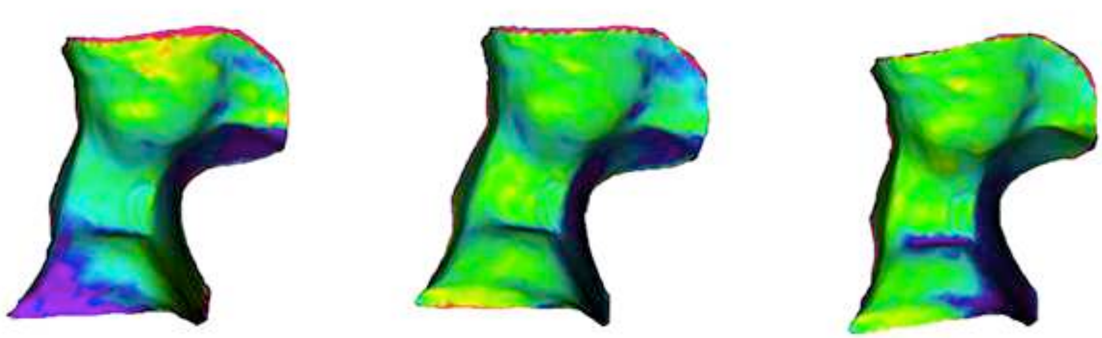


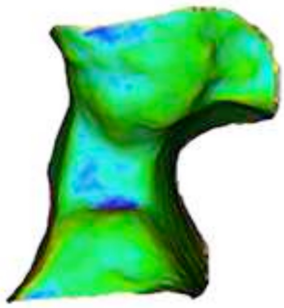
Fig. 2. Deviations between digital calculated cast and scanned milled cast (trueness).

A, Bur12S, 1-step mode. B, Bur12, 1-step mode. C, Bur12 2-step mode. D, Arctica.

Color-coded from -100 µm (blue) to +100 µm (red).



A B C

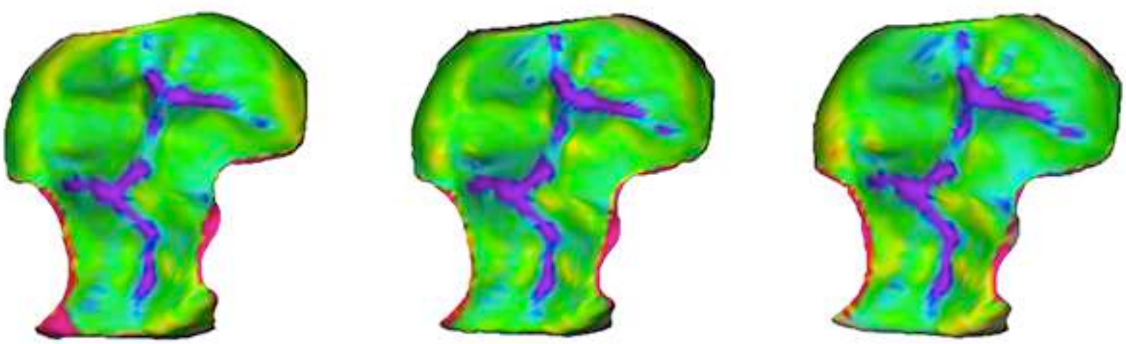


D

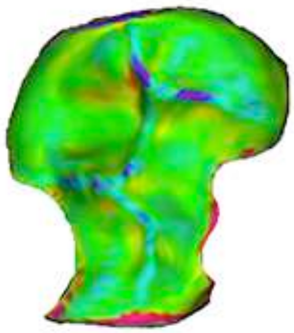
Fig. 3. Deviations between digital calculated casts and scanned milled casts (trueness).

A, Bur12S, 1-step mode. B, Bur12, 1-step mode. C, Bur12 2-step mode. D, Arctica.

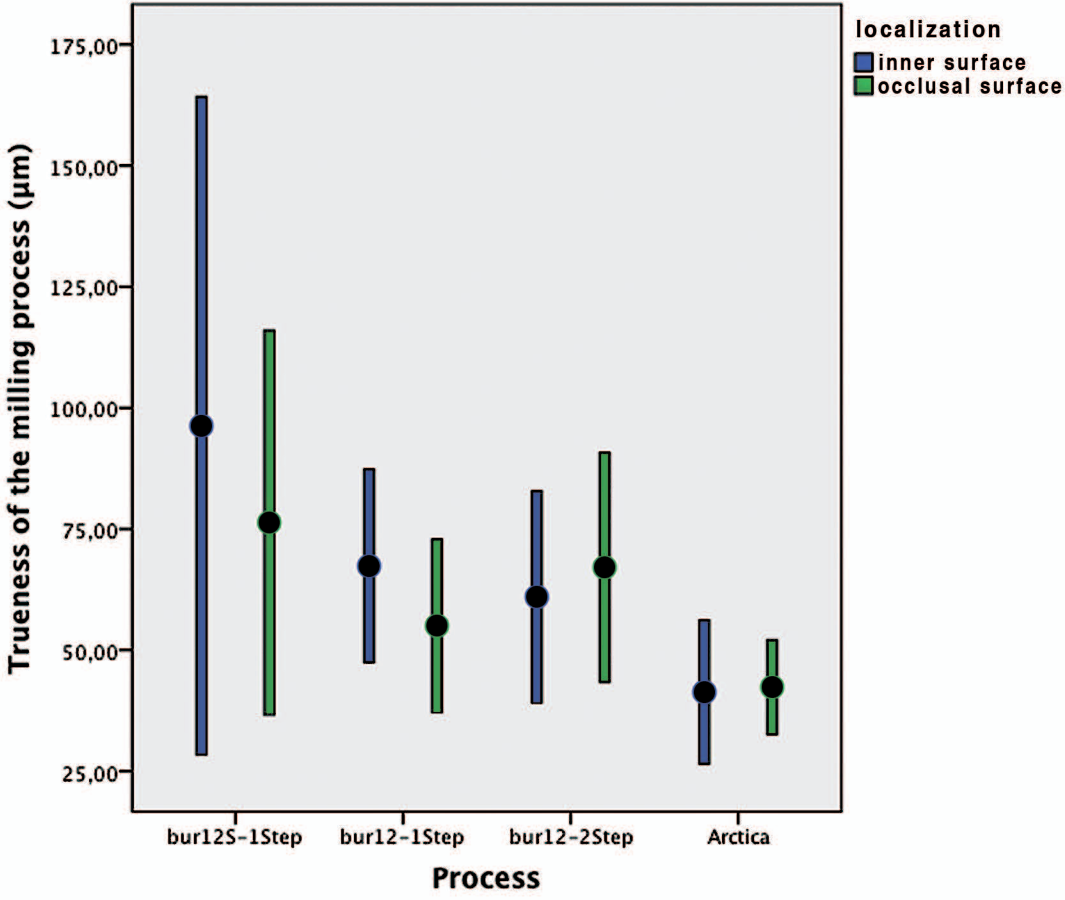
Color-coded from -100 µm (blue) to +100 µm (red).



A B C



D


localization
inner surface
occlusal surface
Trueness of the milling process (µm)
175,00
150,00
125,00
100,00
75,00
50,00
25,00
bur12S-1Step
bur12-1Step
bur12-2Step
Arctica
Process